Óbuda University

Ph.D. Thesis booklet

Modelling of irrecoverable deformation under the action of direct current

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Abstract

The thesis addresses the peculiarities of irrecoverable deformation in electric field. The effect of direct current upon the primary and steady state creep as well as plastic deformation is studied. The action of current leads to the increase of creep deformation in both primary and steady-state portions. Electric impulse applied during plastic deforming results in a jump-wised decrease in the acting stress, i.e. the stress needed to maintain a given level of plastic strain drops instantly as an electric impulse is on. The phenomena listed above have been modeled in terms of the synthetic theory by inserting into its basic formulae a term accounting for the presence of direct current. The analytical results show good agreement with experimental data.

I. Introduction

There are numerous experimental investigations studying the effect of electric current on irrecoverable deformation of low melting alloys.

Chen and Yang (2008, 2010) studied the effect of electric current on the impression creep of Sn, SnPb alloy and Pb and found that the steady state impression velocity increased with the increase of electric current density. They suggested that the momentum exchange between moving electrons and lattice atoms reduced the energy barrier and increased the migration velocity of atoms. Kinney et al. (2009) examined the double shear creep of Sn–Ag–Cu alloy in electric field and showed an increase in the creep rate as a function of current density. Zhao et al. (2012) studied the electromechanical responses of Cu strips. Shao et al. (2012) analyzed the electric-field-assisted diffusional creep in polycrystalline materials.

Of special importance are results provided by Zhao et al. (2014) addressing the effect of direct current upon the creep deformation of pure tin in uniaxial tension. They report an increase in both stages of creep deformation due to the action of current. An analysis of the evolution of microstructures shows that the creep of tin is controlled by dislocation climb over the temperature and stress ranges considered in the experiments. On the other hand, the dislocation climb rate strongly depends on the diffusion of vacancies. It is the action of current that intensifies the vacancy flow via an increase in mass transport due to the momentum exchange between electrons and atoms that, in turn, facilitates the dislocation climb and increases the creep deformation. The other factor affecting the behavior of tin specimens is an increase in temperature due to Joule heating.

The results proposed by Zhao et al. can be summarized as follows:

(i) Both primary and steady-state creep increases with electric current density. In addition, the reduction in primary stage is recorded
(ii) The steady-state creep rate increases linearly with the square of the electric current density.
(iii) Power-law relationship governs the stress dependence of the steady-state creep.
(iv) Electric current has no significant effect on the activation energy and the stress exponent for secondary creep. In electric field, the nature of mechanisms governing creep deformation does not change radically, but the intensity of these mechanisms increases drastically.

Nguyen et al. (2016) investigated the effect of a single pulse of electric current applied during plastic straining of Magnesium AZ31 alloy in uniaxial tension. According to Nguyen's records, as the electric impulse is on, the applied stress undergoes step-wise decrease, stress-drop. The amount of the stress-drop increases near linearly with the electric energy density. Once the electric current is removed from the specimen, the acting stress regains its value on the initial stress-strain curve and the further loading leads to a strain-hardening until fracture. Similar results are reordered by Roh et al. (2014) and Kim et al. (2014) for 5052 Al alloy and advanced high-strength steel, respectively.

Summarizing the researches above, direct current manifests itself in:

(i) Joule heating causing a change in local temperature and resulting in time-dependent plastic deformation;

(ii) the momentum exchange between moving electrons and lattice atoms which reduces the energy barrier and increases the migration velocity of atoms;

(iii) the intensification of the current field assisted sliding rate and diffusional creep.

A literature review shows that the majority of researches focus on the measurement results, suggesting only empirical formulas to describe the irrecoverable deformation in the presence of current. On the other hand, the model I'm proposing, which is developed in terms of the synthetic theory of irrecoverable deformation, accounts for the microstructural changes in material caused by direct current (DC) that affect the progress in irrecoverable straining. In addition, it must be stressed that the formulae for both plastic and creep strain are derived from a single constitutive equation of the synthetic theory.

II. Objectives

My research aims to develop a model of irrecoverable deformation in electric field. The synthetic theory of inelastic deformation is used as a mathematical framework for my investigations. The following phenomena are considered:

a) An increase in the steady steady-state creep rate coupled with DC (Fig. 1.a).
b) An increase in transient creep and the shortening of its duration under the action of current (Fig. 1.b).
c) Stress-drop during plastic deformation with a pulsed electric current (Fig. 1.c).
d) The evolution of loading surface for irrecoverable strains in electrical field.

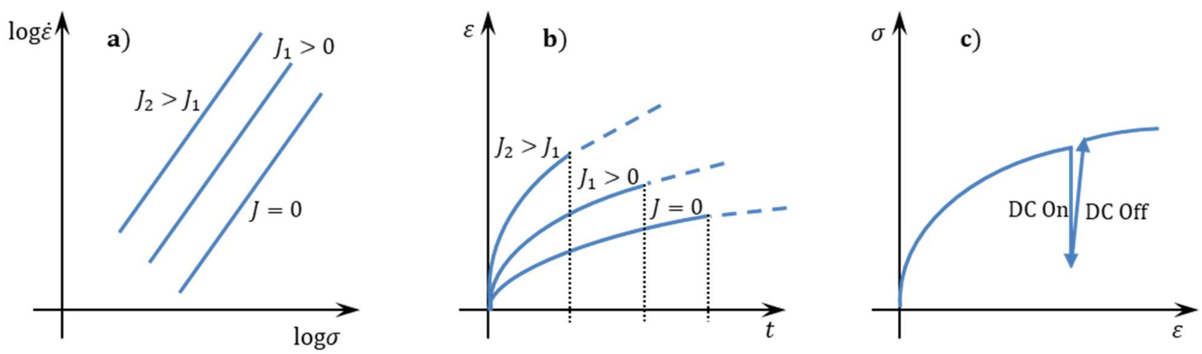

Fig. 1. The effect of DC upon a) steady-state creep rate, b) transient creep, c) plastic straining (J – current density)

III. Theoretical background

As stated above, I model the phenomena shown in Fig. 1 in terms of the synthetic theory.

The synthetic theory of irrecoverable deformation incorporates the Batdorf-Budiansky slip concept and the Sanders flow theory. The theory deals with small plastic or creep deformations of hardening polycrystalline materials (Rusinko, A., & Rusinko, K., 2009,2011).

The theory inherits both the mathematical and the physical nature from the above mentioned concepts. As a mathematical model it satisfies all the requirements imposed on theories of plasticity (Drucker's postulate, the law of deviator proportionality, isotropy postulate, etc.). Similarly to the slip concept, the synthetic theory accounts for the processes occurring on the microlevel of material that governs the progress in plastic/creep deformation.

Of special importance is the fact that the theory utilizes a single notion, irrecoverable (permanent) deformation, and does not make a difference between plastic ("instantaneous") and creep (viscous) strains (Rusinko, A., 2008, 2009). The components of deformation, instant or time-dependent, manifest themselves depending on the loading and thermal regimes.

Following the tendency of unified approaches to model permanent deformation (see e.g. Chaboche et al., 1996 and 1997), the flow rule of the synthetic theory is defined in such a way that all types of deformation, plastic or creep, can be described from the same system of constitutive equations. The universality of this system is based on:

(i) A single constitutive equation gives the relation between microdeformation, crystalline structure defects induced by this deformation, and time. Furthermore, since the synthetic theory is of two-level nature, the macrodeformation is calculated as a sum of slips occurring at the microlevel of the material.

(ii) The specific feature of the synthetic theory consists mainly in the formulation of the hardening rule. The evolution of loading surface is not prescribed a priory, but strongly depends on the hodograph of stress vector, i.e. the loading path governs entirely the evolution of the loading surface.

IV. Results – thesis points

Thesis №1

I have developed a model, in terms of the synthetic theory of irrecoverable deformation, which enables to evaluate the steady-state creep coupled with direct current [1,3].

A great number of investigators have clearly established that the creep deformation of solder materials undergoes significant changes in electric field. To catch the effect the current exerts upon the creep rate, I have extended the constitutive relationships of the synthetic theory by a term containing the current intensity. As a result, I have derived the following relationships for the steady-state creep rate coupled with DC:

(i) Steady-state creep rate as a function of stress under the action of current of different intensities.

(ii) Steady-state creep rate as a function of current intensity at different temperatures.

Thesis №2

I have generalized the synthetic theory of irrecoverable deformation to accurately present the analytical description of the following cases [2]:

(i) The effect of current upon the magnitude and duration of transient creep.

(ii) The effect of a short electric impulse upon plastic straining.

I have extended the rate-integral of the synthetic theory, whose magnitude and temporal relaxation govern the development of transient creep, to relate to DC intensity. As a result I derived the relationships to calculate

(i) the magnitude and duration of transient creep under the action of current of different intensities.

In terms of the synthetic theory extended to the case of the presence of DC, I derived the formula to calculate

(ii) the stress-drop induced by the electric impulse during plastic deforming.

Thesis №3

I have derived the equations that govern the evolution of loading surface [4,5].

I have evaluated the deformation properties of metals in electric field by the thorough analysis of the evolution of the loading surface, in the case of uniaxial tension, for different types of irrecoverable deformation (primary/secondary creep, plastic deformation). I have developed a program that describes the kinetics of the evolution of the loading surface. In addition, I have generalized the results obtained for the case of uniaxial tension to a general proportional stress state. I have shown that the law of proportionality of deviators remains valid in the presence of current as well.

V. Practical effect

In today's complicated electronic devices, thousands of interconnects are integrated on a single printed circuit board. With the trend of further dimensional scaling down of electronic devices, more and more attention has been paid on electromigration induced failure due to aggressive increase of electric current density. The electromechanical response of electrical interconnects becomes an important issue in the reliability of electronic devices. In practical applications, electrical interconnects may suffer to the creep deformation and stress relaxation even at room temperature due to the thermal mismatch stress between electronic components and printed circuit board. Therefore, understanding the creep behavior and deformation mechanism of this kind of solder materials plays a crucial role in practice.

The effect of an electron wind on the mechanical properties of metals is investigated with the ultimate goal of establishing a technique by which the mechanical energy associated with the deformation of a material can be reduced without requiring a significant increase in the material's temperature. Recently, electrically assisted forming technology as an alternative has received rapidly increasing interests from academies and industries. The applied electric current can reduce the flow stress and improve the plastic potential resulting in a lower specific energy and cost.

Thus, the results presented in the dissertation contribute to a more effective modelling of the processes coupled with current flows, and therefore enhances the reliability of microelectronic devices and the optimization of forming technologies through electrical assistance.

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